Appendix IX: Energy Conversion Crosscut

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ENERGY CONVERSION CROSSCUT

Generation IV energy conversion R&D focuses on energy conversion technologies that support implementation of Generation IV reactor systems, either through improved efficiency, reduced costs or enabling new energy products. Energy conversion technologies that optimally couple to the performance characteristics of Generation IV reactors will result in more efficient and cost effective nuclear power systems. Energy conversion components that are smaller or less complex result in reduced plant capital costs, ultimately reducing next generation nuclear electricity costs. For FY 2004 Generation IV Energy Conversion work addresses both the improved electrical conversion technologies that can be developed for the longer-term implementation of the range of Generation IV reactors, and also the analysis of baseline options for power conversion systems for the NGNP. Assessment of power conversion options for NGNP will provide a basis for the initial design studies to be performed as part of the NGNP project. Longer-term studies will be performed to identify the most promising power conversion options for the range of next generation nuclear plants and assess the potential improvements in cycle efficiency or conversion system cost. These studies will lead to scaling demonstration experiments for selected options to provide a validated technology basis for next generation engineering decisions.

1 ENERGY CONVERSION SCOPE – FY2004 AND BEYOND

In FY 2004 and beyond, the scope of the Generation IV Energy Conversion Program will focus on advanced electrical conversion options that have potential to improve system efficiency or reduce capital costs. Generation IV reactor systems are being considered that produce a range of output temperatures. The Very High Temperature Reactor (VHTR) is considering designs for outlet temperatures of 1000 C. The Gas Fast Reactor (GFR), Lead Fast Reactor (LFR) and Sodium Fast Reactor (SFR) are considering designs that result in outlet temperatures in the range of 550-700 C or higher. The Supercritical Water Reactor (SCWR) outlet temperatures are in the range of 400 to 500 C.

With this range of outlet temperatures for Generation IV systems, it is important to consider power conversion options that couple most effectively with system characteristics. Current light-water reactors (LWR) power plants use steam Rankine cycles for electrical generation, which provide efficiencies of about 33%. The steam Rankine cycle is an efficient options at LWR outlet temperatures, but materials and operating conditions become challenging at the higher temperature ranges characteristic of most Generation IV systems. Superheated or supercritical Rankine cycles, which are in use in some coal fired plants, extend the applicable temperature range, but these cycles are not considered applicable to the higher temperature Generation IV reactor conditions. Brayton cycles using inert gas or other working fluids are well matched to the higher temperatures of the Generation IV reactors. Technology developed for combined Brayton cycle gas turbines is commercially available and provides a basis for developing a range of closed cycle Brayton systems for Generation IV. Stirling cycles are generally not considered applicable for the large-scale applications. Although very advanced direct conversion approaches, such as magneto-hydrodynamics, thermal- photovoltaics, or other direct conversion approaches may be developed in the future, the focus of Generation IV power conversion research will be on conversion cycles that can be developed in the time frame of the Gen IV reactors – 15 to 20 years. Supercritical or superheated Rankine cycles will be considered for the SCWR, but since these systems have been developed for coal fired plants, research on these cycles is not considered a high priority for SCWR viability. For the intermediate and higher temperature ranges applicable to most Generation IV systems, Brayton cycles using inert or other gas working fluids are promising technologies for nuclear systems. The focus of the Generation IV power conversion work will be on advanced Brayton cycle options for the intermediate and high temperature reactors.

The development of optimum power conversion technologies for Generation IV systems can be an important component of next generation nuclear plant viability. The cost of electricity from a next generation nuclear plant can be schematically represented as,

Cost ($/kw-hr) = (Capital Cost Recovery + Operating Costs)/(Electrical Output).

Nuclear system capital costs have been a primary factor in nuclear electricity costs. Improvements in plant efficiency, derived from improvements in the power conversion cycle, increase plant output directly, producing more power from the same investment in the nuclear plant. As long as any increased cost in the conversion cycle is relatively small compared to the nuclear plant costs, improvements in cycle efficiency have the same result as direct reductions in plant construction and operating costs. There is significant motivation to investigate improved conversion systems for Generation IV plants.

2 ENERGY CONVERSION RESEARCH AREAS

The Power Conversion crosscut will address advanced conversion cycles that have the potential to lower nuclear electricity costs through either increased efficiency or reduced capital costs. The two primary areas of interest for Generation IV are:

1. High temperature (1000 C) Brayton cycle options for gas cooled systems, and
2. Intermediate temperature (approximately 550-700 C), CO_2 Brayton cycles for GFR and liquid metal systems.

For the high temperature Brayton cycle studies, the focus will be on the development of cost effective options for interstage heating or cooling approaches that provide higher efficiencies with acceptable increases in system complexity. For FY04, the power conversion crosscut will also assess the nearer term power conversion issues involved in defining initial design options for the NGNP power conversion system. This assessment will involve engineering studies to address recuperated Brayton cycle considerations for direct vs. indirect cycle approaches, single and multiple shaft options, and turbine design choices.

For the intermediate temperature range, studies will address supercritical CO_2 (SC CO_2) cycles for the GFR, liquid metal cooled, and MS reactors. These studies will initially focus on viability issues of SC CO_2 turbomachinery design, materials compatibility issues and system economics. Other process heat applications, such as hydrogen production, desalinization, or other industrial process heat uses, could be considered as part of a hybrid electrical cycle and will be considered in systems studies. The power conversion R&D to be performed as part of Generation IV will be coordinated with DOE-EE or other government agencies, universities, and industry where there may be synergisms with non-nuclear programs. In some areas it may be possible to complement or increment ongoing R&D sponsored by other agencies to facilitate the nuclear application.

2.1 Brayton Cycle Options for High Temperature Systems

The high temperature power conversion studies address the development of cost effective electrical conversion options for VHTR, which is capable of both hydrogen production and high efficiency electricity generation. The focus of initial studies is on the development of cost effective options for interstage heating or cooling that provide higher efficiencies without unacceptable increases in system complexity. The initial advanced assessment will include other advanced cycles and working fluids to define the cost benefit relationship of these approaches for energy conversion. This assessment will account for potential improvements in fabrication or construction techniques and improved turbine designs to define cost implications. Initial studies will focus on thermodynamic analysis and turbomachinery design choices, multi-reheat and interstage cooling approaches and costs. Based on these results, small-scale demonstrations of the key technologies will be performed to validate projected performance benefits.

For FY 2004, the power conversion crosscut will also assess the nearer term issues involved in defining initial design options for the NGNP power conversion system. This assessment will involve engineering studies to assess direct vs. indirect cycle approaches, single and multiple shaft options, and turbine design choices for recuperated helium Brayton cycles. These studies will involve systems and component analyses to define configuration and control issues. Based on these results, small-scale experiments will be identified to address direct cycle control issues, turbomachinery design and performance trades, and high temperature interface issues. This effort will be closely coordinated with the materials crosscut and the NGNP design efforts.

2.2 Supercritical CO2 Cycles for Intermediate Temperature Systems

For the intermediate temperature range application, studies will address supercritical CO_2 cycles. The supercritical CO_2 Brayton cycle provides high efficiency at temperatures in the range of 500 to 600 C, potentially providing a better match with projected outlet temperatures of GFR and metal cooled systems. These studies will initially focus on viability issues of SC CO_2 turbomachinery design, materials compatibility issues and system economics. These studies will establish a baseline supercritical CO_2 Brayton design for coupling to Generation IV systems, identify the materials and systems issues and requirements, and perform scaling experiments to demonstrate key technologies and validate analytical models.

3 ENERGY CONVERSION PROGRAM APPROACH

To provide the necessary power conversion viability and performance information to support technology selection and implementation decisions, the R&D effort will proceed in the following general sequence:

1. Power conversion cycle assessments and analysis to determine viability issues and performance potential for the range of promising power conversion cycles.
2. Laboratory scale demonstrations of components and key technologies to validate viability and performance assessments.
3. Pilot plant demonstrations of selected technologies to assess engineering approach and performance.

This sequence of analysis, component development and small scale experiments will provide information for viability assessment and technology selection. For the selected power conversion options, pilot plant scale experiments will demonstrate engineering approaches, confirm performance potential, and provide improved estimates of power conversion system costs.

4 FY 2004 WORK SCOPE

The Generation IV power conversion activities for FY04 address the assessment of the supercritical CO_2 Brayton cycle, and the high temperature helium Brayton cycle options, and the engineering assessment for NGNP power conversion.

FY 2004 Milestones ($0.6 M)

- Complete conceptual design for a nominal 300 MWe Gen IV supercritical CO_2 system for intermediate temperature Gen IV systems
- Complete preliminary designs for CO_2 turbomachinery.
- Complete initial assessment of supercritical CO_2 plant costs
- Develop conceptual design for SC CO_2 cycle scaling demonstration experiments. Establish collaboration with industry.
- Complete conceptual designs for advanced helium Brayton cycles incorporating interstage reheat and cooling features. Perform preliminary cost studies to assess cost –benefit of advanced designs.
- Evaluate electrical energy conversion options and configurations for NGNP. Establish an Industry, University, Laboratory team consisting of the necessary technical expertise to support the NGNP power conversion assessment.
- Identify key technology and system requirements for high temperature Brayton cycles. Perform trade studies to address direct vs. indirect cycle issues, single and multiple shaft turbomachinery considerations, and reactor to conversion cycle intermediate heat exchanger issues.

- Develop a preliminary plan for the detailed evaluation of key technical issues to support the development of conceptual designs for the NGNP electrical conversion system.

FY 2004 Performance Measures

Complete conceptual designs for CO_2 cycles that could provide cycle efficiencies of 40 % or more from inlet temperatures above 500 C, and He Brayton cycles that provide 55 % or more from inlet temperatures of 1000 C.

5 FY 2005 WORK SCOPE

The FY05 power conversion work completes the initial assessment of the SC CO_2 cycle and the high temperature helium Brayton cycle options and the engineering assessment of NGNP power conversion options.

FY 2005 (Target Budget – $0.60 M)

- Complete preliminary system design for 300 MWe supercritical CO_2 commercial cycle.
- Develop preliminary design for scaled SC CO_2 demo experiment, and develop initial cost and schedule estimates.
- Develop advanced Brayton cycle technology demonstration requirements and preliminary plan for demonstration experiments.

FY 2005 Milestones (Required Budget – $5.0 M)

- Develop final design and initiate fabrication activities for SC CO_2 lab scale demonstration experiment, involving industry collaboration for turbomachinery design and fabrication.
- Complete engineering model for the simulation of supercritical CO2 dynamic response
- Develop final design for electrically heated He (or other working fluid) advanced Brayton cycle demonstration experiment, including industrial partner for turbomachinery.
- Continue materials and fabrication R&D to support test component fabrication. Construct selected IHX for scaling demonstration experiments.

FY 2005 Performance Measures

Complete assessment of supercritical CO2 cost effectiveness for cycle efficiencies greater than 40% at inlet temperature above 500 C. Establish cost effectiveness of intersatge heated and cooled Brayton cycles, and performance potential of 55 % or more from inlet temperatures of 1000 C.

6 TEN YEAR PLAN

During the FY06 through FY13 period, the Generation IV Energy Conversion crosscut activities will establish requirements, complete technology assessments, perform key technology development efforts, and complete pilot plant level demonstrations of the selected power conversion technologies necessary to support technology decisions.

The major milestones for Energy Conversion for the out years (FY2006 through FY2013) for Required and Target budgets are summarized below.

FY 2006 (Target Budget)

- Initiate fabrication of lab scale SC CO_2 demonstration experiments
- Perform engineering analysis for interstage heated and/or cooled He Brayton

FY 2006 Milestones (Required Budget)

- Construct electrically heated SC CO_2 demonstration experiments.
- Initiate fabrication of electrically heated He Brayton cycle demonstration components.
- Perform IHX component tests to support demonstration tests
- Assess potential for improvements in fabrication techniques and improved turbine designs

FY 2007 (Target Budget)

- Continue fabrication of components for lab scale SC CO_2 demonstration tests
- Perform SC CO_2 materials, component tests
- Complete preliminary design for He Brayton demo experiment.

FY 2007 Milestones (Required Budget)

- Initiate electrically heated SC CO_2 demonstration experiments.
- Construct electrically heated He Brayton cycle demonstration experiments.
- Complete design and initiate fabrication of improved turbine components for engineering demonstration
- Complete report on technical basis for advanced electrical conversion options for Gen IV systems.

FY 2008 (Target Budget)

- Complete construction of components and construction of lab scale SC CO_2 demonstration tests.

FY 2008 Milestones (Required Budget)

- Continue initial lab scale SC CO_2 test series
- Design of improved SC CO_2 turbine and compressor designs for next stage tests
- Initiate fabrication of improved SC CO_2 turbo machinery components.
- Initiate lab scale high temperature He Brayton test series.

FY 2009 (Target Budget)

- Perform initial lab scale SC CO_2 test series.
- Initiate He Brayton cycle component fabrication

FY 2009 Milestones (Required Budget)

- Complete construction of advanced design components for SC CO_2 system and initiate testing.
- Continue initial series of lab scale He Brayton cycle tests.
- Conceptual design for pilot scale SC CO_2 demonstration experiment.

FY 2010 (Target Budget)

- Complete SC CO_2 testing with initial design components
- Continue component fabrication for lab scale He Brayton cycle tests

FY 2010 Milestones (Required Budget)

- Perform SC CO_2 lab scale tests with improved design components
- Continue lab scale He Brayton tests
- Initiate design and fabrication of alternative He Brayton components
- Design Pilot Scale SC CO_2 demonstration

FY 2011 (Target Budget)

- Design and fabricate improved SC CO_2 components for lab scale system.
- Continue fabrication of He Brayton cycle lab scale components.

FY 2011 Milestones (Required Budget)

- Construct pilot scale components for SC CO_2 system
- Fabricate alternative components and initiate tests for lab scale He Brayton cycle.
- Perform materials and support component test for pilot scale experiments

FY 2012 (Target Budget)

- Continue fabrication of improved SC CO_2 lab scale components
- Complete component fabrication for He Brayton lab scale tests

FY 2012 Milestones (Required Budget)

- Complete construction of pilot scale demonstration components for SC CO_2 system.
- Complete lab scale He Brayton demo with alternative components and initiate testing
- Initiate conceptual design for pilot scale He Brayton demo

FY 2013 (Target Budget)

- Initiate improved SC CO_2 lab scale tests
- Initiate lab scale He Brayton system tests

FY 2013 Milestones (Required Budget)

- Initiate pilot scale SC CO_2 demonstration experiments
- Complete final design for pilot scale He Brayton cycle components and demonstration tests

7 PERFORMANCE MEASURES FY2005 – FY2009

Performance measures for the FY 2006 to FY2013 period measure success in demonstrating advanced electrical conversion approaches that provide significant efficiency and cost benefit improvements for Gen IV systems. For the required budget level, these R&D activities will demonstrate SC CO2 conversion systems that provide significant efficiency or capital cost improvements over steam Rankine or standard Brayton cycles at the pilot scale. For the He Brayton small scale experiments at the 0.5 to 1 MWe range will be completed. The capital cost implications of these conversion systems will be estimated to determine the net cost benefit of these advanced conversion technologies.

For the Target budget level, the performance measure addresses a single approach (SC CO2) at a lab scale (the smallest credible and practical demonstration size). For the He Brayton cycle, small scale components will be designed and tested

FY 2006 – FY 2013 Performance Measures – Required Budgets

Complete demonstration of SC CO_2 conversion cycles at a pilot scale that project to commercial scale cycle efficiencies of 40 % or more from inlet temperatures above 500C. Demonstrate interstage heated cooled He cycle options at a lab scale that project to efficiencies of greater than 55 % at temperatures of 1000 C.

FY 2006 – FY 2013 Performance Measures – Target Budgets

Complete lab (small) scale demonstration of supercritical CO_2 cycle that project to engineering scale efficiencies of 40 % or more for coolant inlet temperatures above 500 C.

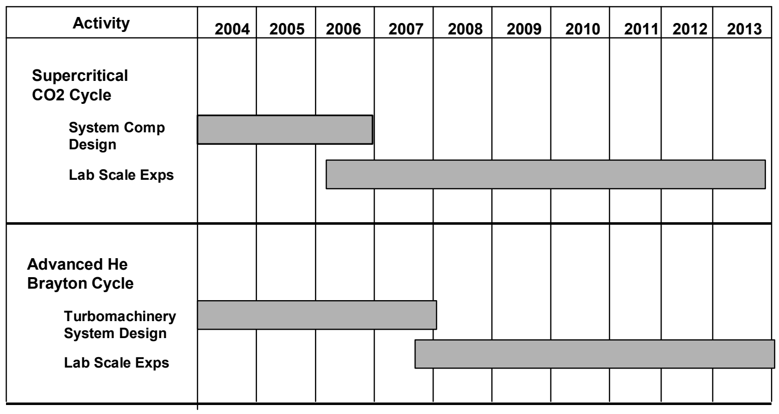
Table 1 Summary of Gen IV Energy Conversion Milestones for Required and Target Budgets

Year	Energy Conversion Milestones Required Budget	Req'd Budget (M$)	Energy Conversion Milestones Target Budget	Target Budget (M$)
FY04			SC CO2 cycle Brayton system and turbomachinery preliminary design SCCO2 cycle cost studies Complete He Brayton cycle cost benefit assessment NGNP power conversion technology assessment	
FY05	Complete SC CO_2 300 MWe system design Initiate SC CO_2 scaled demo fabrication Design advanced Brayton demo Advanced IHX , test component fabrication		Complete conceptual design for SC CO_2 Preliminary design for SC CO_2 demo experiment He advanced Brayton turbo machinery design	
FY06	Construct SC CO_2 demonstration experiments. Initiate construction of interstage heated and cooled He Brayton demo exps. Perform component tests for CO2 conditions Assess improved turbine designs		Initiate fabrication for lab scale SC CO_2 demo Engineering analysis for interstage heated and / or cooled He Brayton	
FY07	Initiate SC CO_2 lab scale demonstration experiments on initial designs Improved turbine designs for SC CO2 pilot plant demo Complete construction of He Brayton scaled demonstration experiments Advanced IHX component and materials tests		Continue fabrication of SC components for lab scale exps SC CO_2 materials, component tests Preliminary design for He Brayton demo experiment	
FY08	Complete initial lab scale tests SC CO_2 Design and fabricate improved SC CO_2 turbine/component designs for engineering demo tests		Complete construction of SC CO_2 lab scale experiment	

	Initiate small scale He Brayton cycle tests Advanced component and materials for pilot scale demo			
FY09	Construct advanced design SC CO_2 turbine components Complete Phase 1 He Brayton small scale tests Conceptual design for SC CO_2 pilot demonstration		Perform lab scale testing of SC CO_2 demo Initiate He Brayton cycle lab scale component fabrication	
FY10	Perform SC CO_2 small scale tests with improved design components Continue lab scale He Brayton testing Initiate alternative He Brayton component fabrication Complete design for pilot scale SC CO_2 demonstration		Complete SC CO_2 testing with initial components Continue lab scale He Brayton component fabrication	
FY11	Construct pilot scale SC CO_2 components Fabricate alternative lab scale He Brayton components and initiate tests		Design and fabricate improved lab scale SC CO_2 components Continue lab scale He component fabrication	
FY12	Complete construction of pilot scale SC CO_2 components Complete lab scale He Brayton tests with alternative components Conceptual design for pilot scale He Brayton test		Continue fabrication of improved SC CO_2 lab scale components Complete lab scale He Brayton component fabrication	
FY13	Initiate pilot scale SC CO_2 demo experiments Complete final design for pilot scale He Brayton cycle demonstration		Perform improved component SC CO_2 lab scale tests Initiate lab scale He Brayton system tests	

Generation IV Power Conversion Program

Target Budget



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Required Budget